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On-Off Control Based Multi-Frequency Multi-Load Inverter Configuration for Induction Cooking Application

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Abstract- Multiple load induction cooking application is in much demand today. This paper presents a Full bridge inverter operated at multiple frequencies for powering multiple induction heating loads. ADC control and PDM are employed. Three induction cooking loads are used. Each induction cooking load and one resonant capacitor forms a series resonant circuit. Two series resonant load circuits are simultaneously powered in one half cycle and another load is powered during next half cycle. Each load is operated at a constant frequency. Independent load power control is provided. The operation of the proposed inverter and simulation results are presented.
Keywords – Series resonant inverter, Induction heating, Asymmetrical duty cycle control

I. INTRODUCTION

Induction heating has become a widely used heating method in domestic and industrial applications due to advantages like its cleanliness, controllability and safety etc. High frequency ac voltage is applied to an induction coil and eddy currents are induced in the vessel or the material placed over it. This develops heat in the material. The heat generated concentrates in a peripheral layer at a skin depth (δ),

$$\delta = \sqrt{\frac{\rho}{\pi \mu f_s}} \qquad = \frac{1}{2\pi\sqrt{L_{eq1} C_{r1}}} \qquad (1)$$

where, ρ is electrical resistivity and μ is magnetic permeability of the load material, and f_s is switching frequency of the inverter. Resonant inverter is widely used to supply high frequency AC input to the coil. Quasi resonant, half-bridge, and full-bridge inverters [1]-[4] are mostly used. Full-bridge inverter is most suitable for high power applications. Power control is obtained using different techniques. With Pulse Amplitude Modulation (PAM) control, source voltage amplitude is varied to control the output power. With PFM control, the switching frequency is varied over a certain range to obtain power control. Phase shift control (PSC) technique is also used for output power control. A hybrid power control technique which uses pulse-density-modulation (PDM) [6]-[7] and phase-shift-modulation (PSM) is proposed in [5]. With asymmetrical voltage cancellation (AVC) and asymmetrical duty cycle (ADC) control soft switching is improved [8].

In multiple-load induction cooking applications, inverters with less number of components and control techniques to provide independent control of the loads and soft switching for improving the efficiency are the main requirements. A two load system powered from single inverter is proposed in [9], which uses variable switching frequency control. It uses several resonant capacitors in parallel and electro mechanical switches. In [10], a three leg inverter with one leg common for two loads is proposed. Independent and simultaneous control of both loads is provided. AVC technique is used for control of the inverter.

This paper proposes a multi-frequency full-bridge inverter configuration for multiple-load induction cooking application. Single full-bridge inverter powers three loads. The proposed configuration provides independent control of each load, high efficiency, reduced components count, and less complexity. In this configuration, ADC control and PDM control techniques are used.

I. PROPOSED SYSTEM

The circuit diagram of proposed inverter configuration is shown in Fig. 1. It consists of a full-bridge inverter. Q_1, Q_2, Q_3 and Q_4 are the MOSFET switching devices and D_1, D_2, D_3 and D_4 are respectively the body diodes of these MOSFETs. The full-bridge inverter is supplied from a dc voltage of V_{DC}.

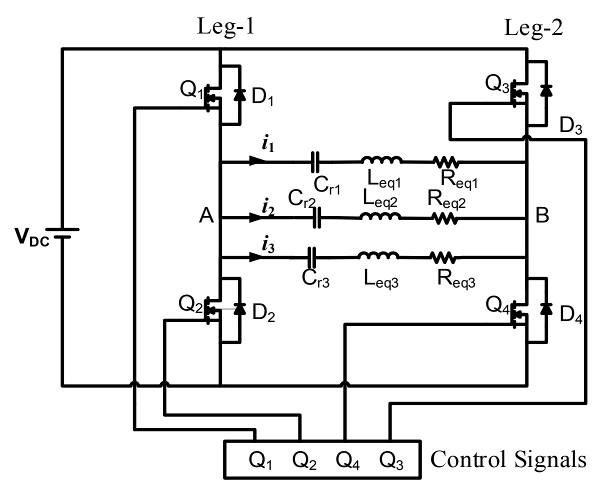


Fig. 1 Proposed inverter configuration

Induction heating load is modelled as series combination of an equivalent inductance and resistance. One capacitor is connected in series and it makes a series resonant circuit. Three resonant induction heating loads are connected in parallel across the inverter output terminals 'A' and 'B'. Load-1 consists of L_{r1}, R_{eq1} and C_{r1}, which are inductance and equivalent load resistance of the load-1, and external resonant capacitor connected respectively. Similarly, load-2 consists of L_{r2}, $R_{eq2}$and C_{r2} and load-3 consists of L_{r3}, R_{eq3} and C_{r3}. In each cycle of operation (T = 1 msec), during the interval of t_1, load-1 and load-2 are powered. Each leg of the inverter is controlled with ADC method. In the remaining half cycle, load-3 is powered. For power control, PDM technique is used.

II. Principle of Operation

Switching frequencies corresponding to load-1, load-2 and load-3 are 22 kHz, 88 kHz and 352 kHz respectively. Resonant frequencies of load-1, load-2 and load-3 are expressed as $f_{r1}=\frac{1}{2\pi\sqrt{L_{eq1}C_{r1}}}$, $f_{r2}=\frac{1}{2\pi\sqrt{L_{eq2}C_{r2}}}$ and $f_{r3}=\frac{1}{2\pi\sqrt{L_{eq3}C_{r3}}}$ respectively. These resonant frequencies are selected to be slightly less than the corresponding switching frequencies. The different parameters of the proposed inverter configuration is shown in Table. 1. Here, $L_{eq1} > L_{eq2} > L_{eq3}$ and $C_{r1} > C_{r2} > C_{r3}$ and $f_{s1} < f_{s2} < f_{s3}$.

TABLE 1 PARAMETERS OF PROPOSED INVERTER

Parameter	Value
DC voltage, V_{dc}	50 V
Equivalent resistance of load-1, R_{eq1}	4 Ω
Equivalent inductance of load-1, L_{eq1}	159.25 uH
Equivalent resistance of load-2, R_{eq2}	4 Ω
Equivalent inductance of load-2, L_{eq2}	39.81 uH
Equivalent resistance of load-3, R_{eq3}	4 Ω
Equivalent inductance of load-3, L_{eq3}	9.953 uH
Resonant capacitor of load-1, C_{r1}	0.398 uF
Resonant capacitor of load-2, C_{r2}	0.1 uF
Resonant capacitor of load-3, C_{r3}	0.025 uF
Switching frequency, f_{s1}	22 kHz
Switching frequency, f_{s2}	88 kHz
Switching frequency, f_{s3}	352 kHz

The equivalent circuits of the resonant loads at different frequency components are shown in Fig. 2. When the inverter is operated at f_{s1}, X_{cr2} and X_{cr3} are larger compared to X_{cr1}. Where $\left|X_{C_r}\right| = \frac{1}{2\pi f_S C_r}$. C_2 and C_3 can be considered as open circuits as shown in Fig. 2a. Hence, the current components around f_{s1} mainly flow through R_{eq1}, L_{r1} and C_{r1}. The impedance of current path is

$$Z_{eq1} = R_{eq1} + j\left(2\pi f_{s1}L_{r1} - \frac{1}{2\pi f_{s1}C_{r1}}\right)$$

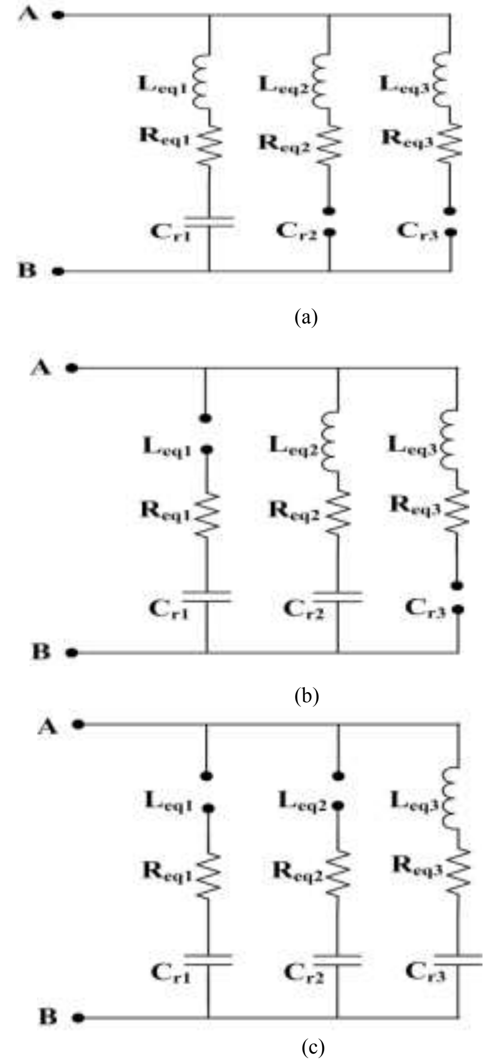


Fig. 2 Equivalent circuit of the loads at different frequencies
a. $f = f_{s1}$
b. $f = f_{s2}$
c. $f = f_{s3}$

When the inverter is operated at f_{s2}, X_{cr3} is larger compared to X_{cr1} and X_{cr2}. Hence C_3 can be considered as open circuit. Also X_{Leq1} is also larger and can be considered as an open circuit as shown in Fig. 2b. $\left|X_{L_{eq}}\right| = 2\pi f_s L_{eq}$ Hence, the current components around f_{s2} mainly flow through R_{eq2}, L_{eq2} and C_{r2}. The impedance of the current path is,

$$Z_{eq2} = R_{eq2} + j\left(2\pi f_{s2}L_{eq2} - \frac{1}{2\pi f_{s2}C_{r2}}\right)$$

When the inverter is operated at f_{s3}, X_{Leq1} and X_{Leq2} are larger and can be considered as open circuit as shown in Fig. 2c. Hence, the current components around f_{s3} mainly flow through R_{eq3}, L_{eq3} and C_{r3}. The impedance of the current path is,

$$Z_{eq3} = R_{eq3} + j\left(2\pi f_{s3}L_{eq3} - \frac{1}{2\pi f_{s3}C_{r3}}\right)$$

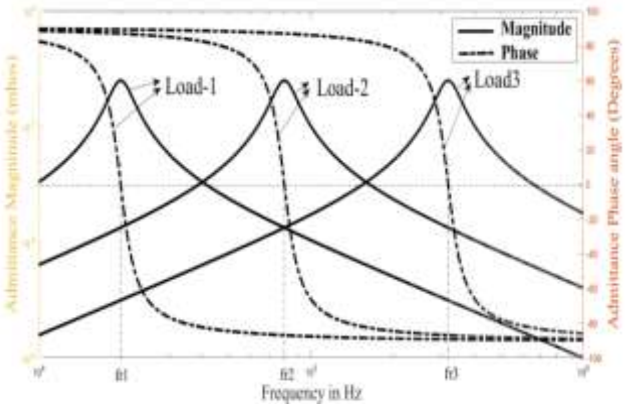


Fig. 3 Admittance characteristics of the loads

Admittance characteristics of the three loads are shown in Fig. 3. At resonant frequencies of individual loads, magnitude of respective tank admittances is maximum and corresponding phase angles are zero.

III. OUTPUT POWER CONTROL

In the proposed inverter configuration, a full-bridge inverter is used. Three induction cooking resonant loads are connected in parallel across the inverter output terminals ‘A’ and ‘B’. In an interval of ‘t_1’ load-1 and load-2 are powered. During next interval ‘t_2’ load-3 is powered. $t_1 = t_2 = T/2$, where T= 1 msec. The switching pulses of inverter devices v_{g1}, v_{g2}, v_{g3} and v_{g4} are shown in Fig. 4. During the interval of ‘t_1’, leg-1 devices, S_1 and S_3 are operated at a switching frequency of f_{s1}. These devices are controlled with ADC control technique. Duty cycle of this operation $d_1= t_{on1}/(t_{s1}/2)$, where $t_{s1}=1/f_{s1}$ and t_{on1} is the on duration of v_{g1}. Leg-2 devices, S_3 and S_4 are operated at a switching frequency of f_{s2}. These devices are also controlled with ADC control technique. The corresponding duty cycle $d_2= t_{on2}/(t_{s2}/2)$, where $t_{s2}=1/f_{s2}$ and t_{on2} is the on duration of v_{g2}.

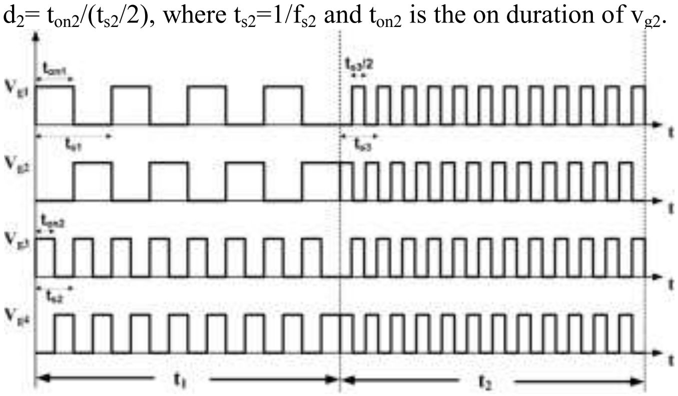


Fig. 4 Switching pulses of inverter devices at maximum duty cycles

Now inverter output voltage V_{AB} contains both f_{s1} and f_{s2} components. Load-1 and load-2 allows only f_{s1} and f_{s2} current components respectively. Current in load-3 is negligibly small. The magnitude of load-1 and load-2 currents can be varied independently by changing the corresponding duty cycles d_1 or d_2. Hence the output current and thereby load powers can be controlled independently.

Fig. 5 Switching pulses of inverter devices at reduced duty cycles

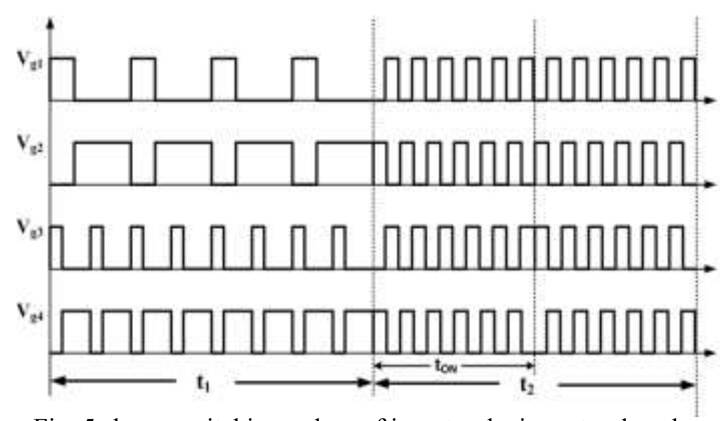


Fig. 5 shows switching pulses of inverter devices at reduced duty cycles. Output power is the power consumed by the equivalent resistances of induction heating loads. Load-1 output power is expressed as,

$$P_{o1}=\left(\frac{2V_{dc}^{2}\cos^{2}\phi_1}{\pi^2 R_{eq1}}\cos^2\frac{\theta_1}{2}\right)\frac{t_1}{T} \quad (2)$$

where,

$$\phi_1=\tan^{-1}\left(\frac{2\pi f_{s1}L_{eq1}-\frac{1}{2\pi f_{s1}C_{r1}}}{R_{eq1}}\right) \text{ and } \theta_1=\left(\frac{t_{s1}}{2}-t_{on1}\right)\left(\frac{2\pi}{t_{s1}}\right) \text{ is the}$$

control angle.

Similarly output power of load-2 is expressed as

$$P_{o2}=\left(\frac{2V_{dc}^{2}\cos^{2}\phi_2}{\pi^2 R_{eq2}}\cos^2\frac{\theta_2}{2}\right)\frac{t_1}{T} \quad (3)$$

where,

$$\phi_2=\tan^{-1}\left(\frac{2\pi f_{s2}L_{eq2}-\frac{1}{2\pi f_{s2}C_{r2}}}{R_{eq2}}\right) \text{ and } \theta_2=\left(\frac{t_{s2}}{2}-t_{on2}\right)\left(\frac{2\pi}{t_{s2}}\right) \text{ is}$$

the control angle.

During the interval t_2, both legs of the inverter are operated at same frequency f_{s3}. As shown in Fig. 4, the switching pulses of inverter devices v_{g1}, v_{g2}, v_{g3} and v_{g4} are operated with 50 % duty cycle. During normal operation, v_{g1} and v_{g4} are in phase and v_{g2} and v_{g3} are in phase. Same leg device pulses are complementary of each other. Hence the output voltage is a square wave of frequency f_{s3} and load-3 conducts this current. In other two loads currents are negligibly small. The power control is achieved using PDM during this interval. This is obtained using phase-on control as shown in Fig. 6. This figure shows switching pulses of inverter devices, inverter output voltage V_{AB} and current in load-3 during interval-2.

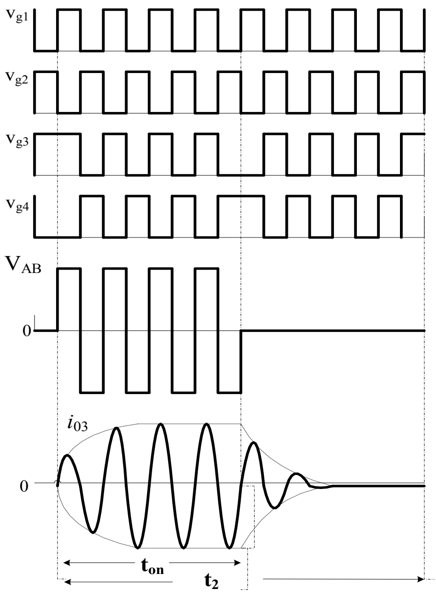


Fig. 6 Switching pulses of inverter devices, inverter output voltage V_{AB} and current in load-3 during PDM control

The switching pulses are applied for an interval of t_{on} and V_{AB} is full square wave as shown in Fig. 6. Sinusoidal current i_{o3} of frequency f_{s3} flows through load-3. At the end of t_{on}, v_{g3} and v_{g4} are inverted, which makes V_{AB} to be zero and thereby the output current is zero. The duty cycle of this PDM control is $d_3=t_{on}/t_3$. Hence by changing d_3, load-3 power can be controlled independently. The output power is expressed as

$$P_{o3}=I_{o3}^2\ R_{eq3}\frac{t_{on}}{T} \tag{4}$$

where, I_{o3} is the r.m.s. value of load-3 current and t_{on} is the duration of output voltage pulses.

IV. SIMULATION RESULTS

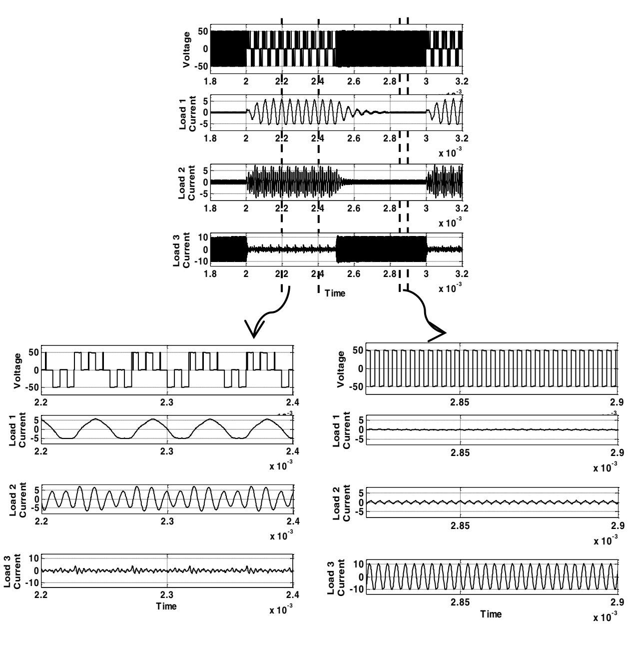


Fig. 7 Simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1 = d_2 = d_3 = 0.9$

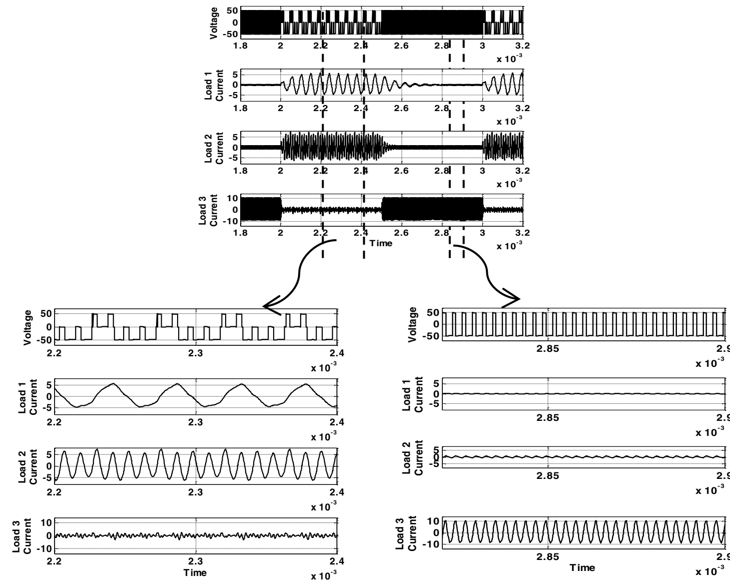


Fig. 8 Simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1= d_2= 0.5$ and $d_3 = 0.9$

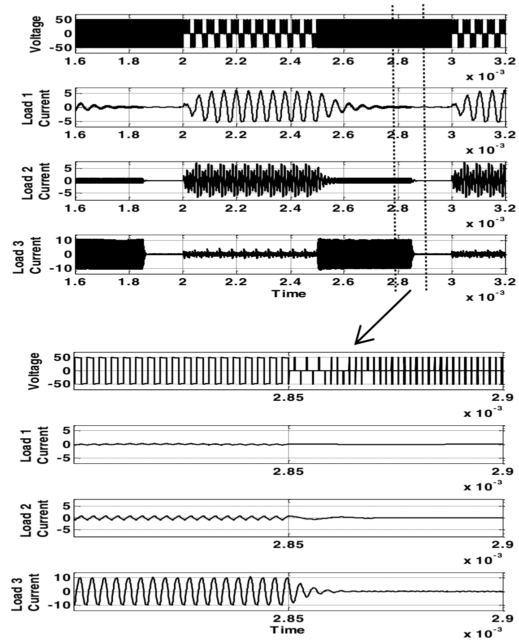
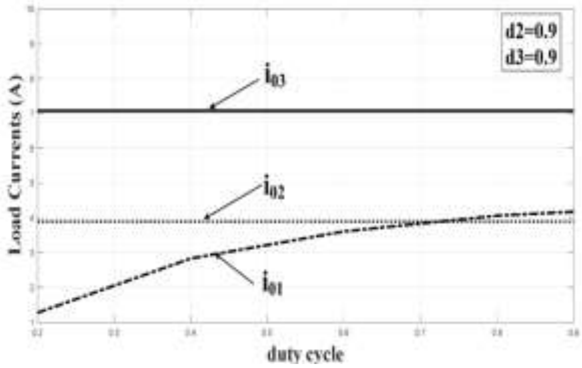


Fig. 9 Simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1 = d_2 = 0.9$ and $d_3= 0.7$

The proposed inverter configuration has been simulated and the simulation results are shown in Figs.7-9. Fig. 7 shows simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1 = d_2 = d_3 = 0.9$. Fig. 8 shows simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1= d_2= 0.5$ and $d_3 = 0.9$. Fig. 9 shows simulation waveforms of V_{AB}, i_{o1}, i_{o2} and i_{o3} for $d_1 = d_2 = 0.9$ and $d_3= 0.7$.

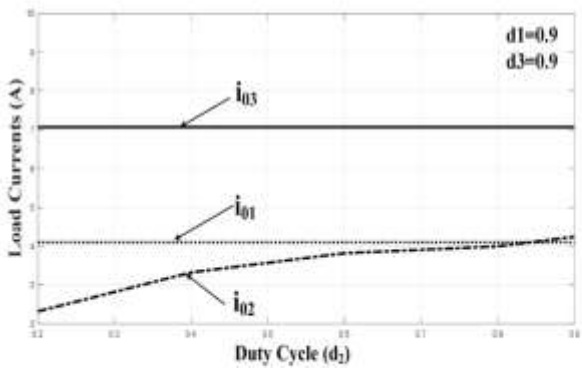
Fig. 10.a shows the variation of load currents when duty cycle d_1 is varied with d_2 and d_3 kept constant at 0.9. It is observed that i_{o2} and i_{o3} are remaining constant while i_{o2} is varying with d_1. Fig. 10.b shows the variation of load currents when duty cycle d_2 is varied with d_1 and d_3 kept constant at 0.9. Only i_{o2} varies when d_2 is changed and other load current remain at constant values. Similarly d_3 controls load-3 current without

affecting other load currents. This shows independent control of all three loads.



d_1

(a)



(b)

Fig. 10 Variation of load currents with
a. load-1 duty cycle d_1
b. load-2 duty cycle d_2

V. CONCLUSION

A multi-frequency full-bridge inverter configuration for multiple-load induction cooking application is proposed. Three induction heating loads are powered from single inverter. The loads are operated at different frequencies. ADC control and PDM control with phase-on technique have been used. Analysis and simulation results are presented. Independent control of loads is achieved. The component count is less. Sinusoidal output currents and square wave or asymmetrical output voltages facilitate soft switching operation and improves the efficiency. The proposed configuration provides independent control of each load, high efficiency, reduced components count, and less complexity

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